



# Solar Spectrum and Intensity Analysis Under Venus Atmosphere Conditions for Photovoltaics Operation

<sup>1</sup>Jet Propulsion Laboratory - California Institute of Technology  
<sup>2</sup>MicroLink Devices  
<sup>3</sup>University of Illinois Urbana-Champaign  
<sup>4</sup>California Institute of Technology

Jonathan Grandidier<sup>1</sup>, Alexander Kirk<sup>2</sup>, Mark L. Osowski<sup>2</sup>, Shizhao Fan<sup>3</sup>, Minjoo L. Lee<sup>3</sup>, Pawan Gogna<sup>1</sup>, Margaret Stevens<sup>1</sup>, Phillip Jahelka<sup>4</sup>, Giulia Tagliabue<sup>4</sup>, Harry A. Atwater<sup>4</sup> and James A. Cutts<sup>1</sup>

Jonathan Grandidier PhD, Technologist, 1<sup>st</sup> June 2019  
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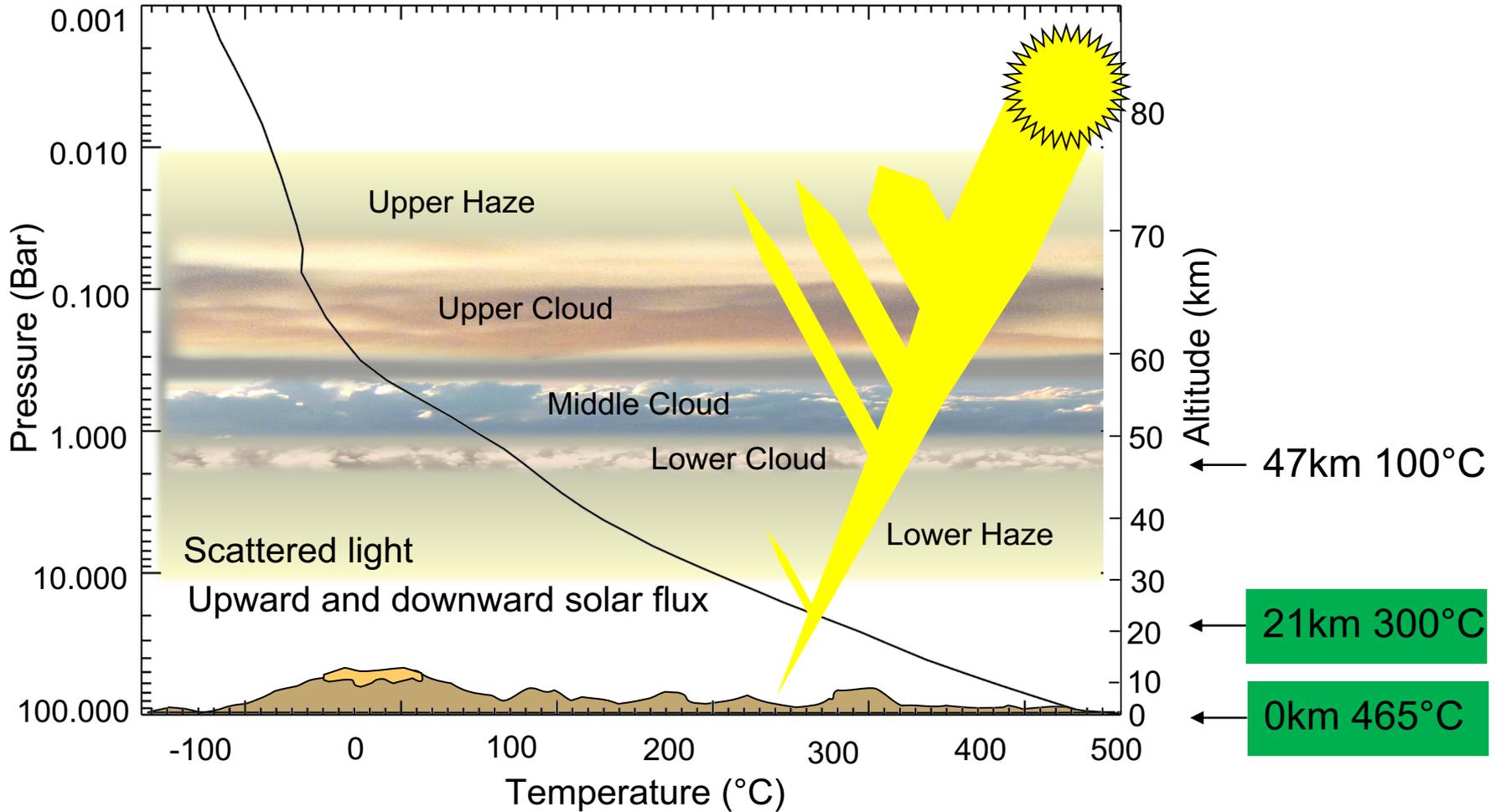
**Jet Propulsion Laboratory**  
California Institute of Technology

# Outline

- Venus atmosphere and solar illumination
- Solar cell performance under Venus temperature and solar spectrum
- Lifetime testing for survivability at Venus
- Solar cell modelling and optimization
- Conclusion

# Venus atmosphere and solar illumination

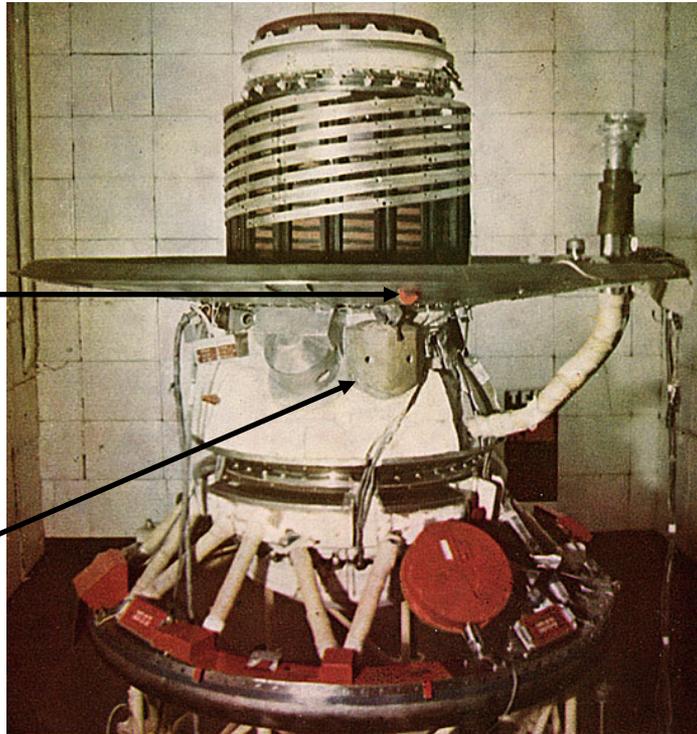
Courtesy David Crisp - JPL



Goal: Solar cell operates at 21km altitude and at the surface of Venus

# Venus atmosphere and solar illumination

Venera-11 descent module



View of a plain near Phoebe Regio from Venera 13, taken on 1 March 1982.



Photometer measurements from Venera 11 and Venera 13 are used to estimate available solar power.

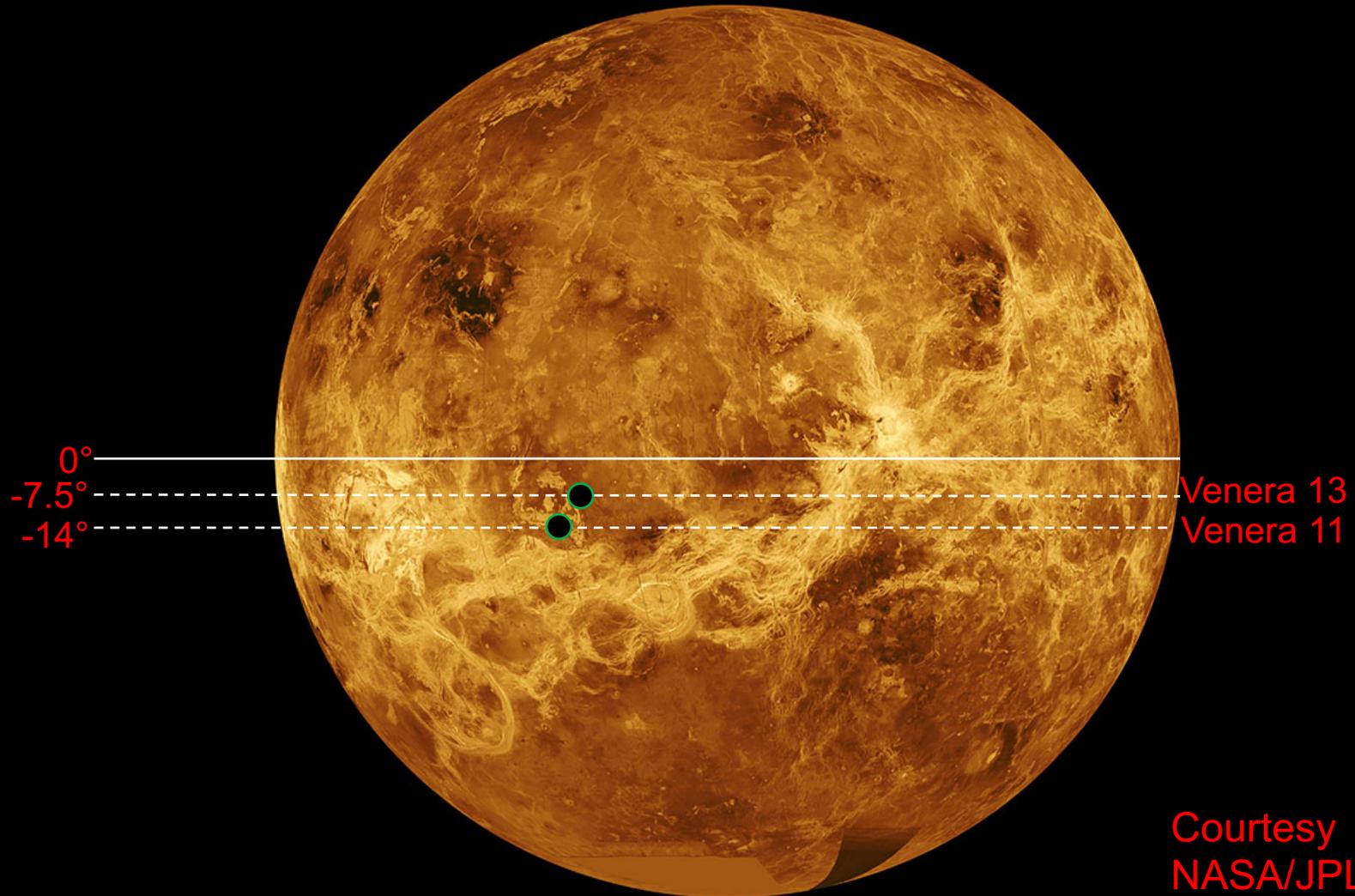
Courtesy Don P. Mitchell

# Venus atmosphere and solar illumination

Venus (Hunten, Colin, Donahue, and Moroz, Eds., 1983) - Table II of Larry Colin's chapter (Chapter 2)

Venera 11 entered at -14 degrees latitude at 11:10 AM local solar time (solar zenith angle 17 degrees) on December 25<sup>th</sup> 1978.

Venera 13 entered at -7.5 degrees latitude at 9:27 AM local time (solar zenith angle 38 degrees) on March 1<sup>st</sup> 1982.

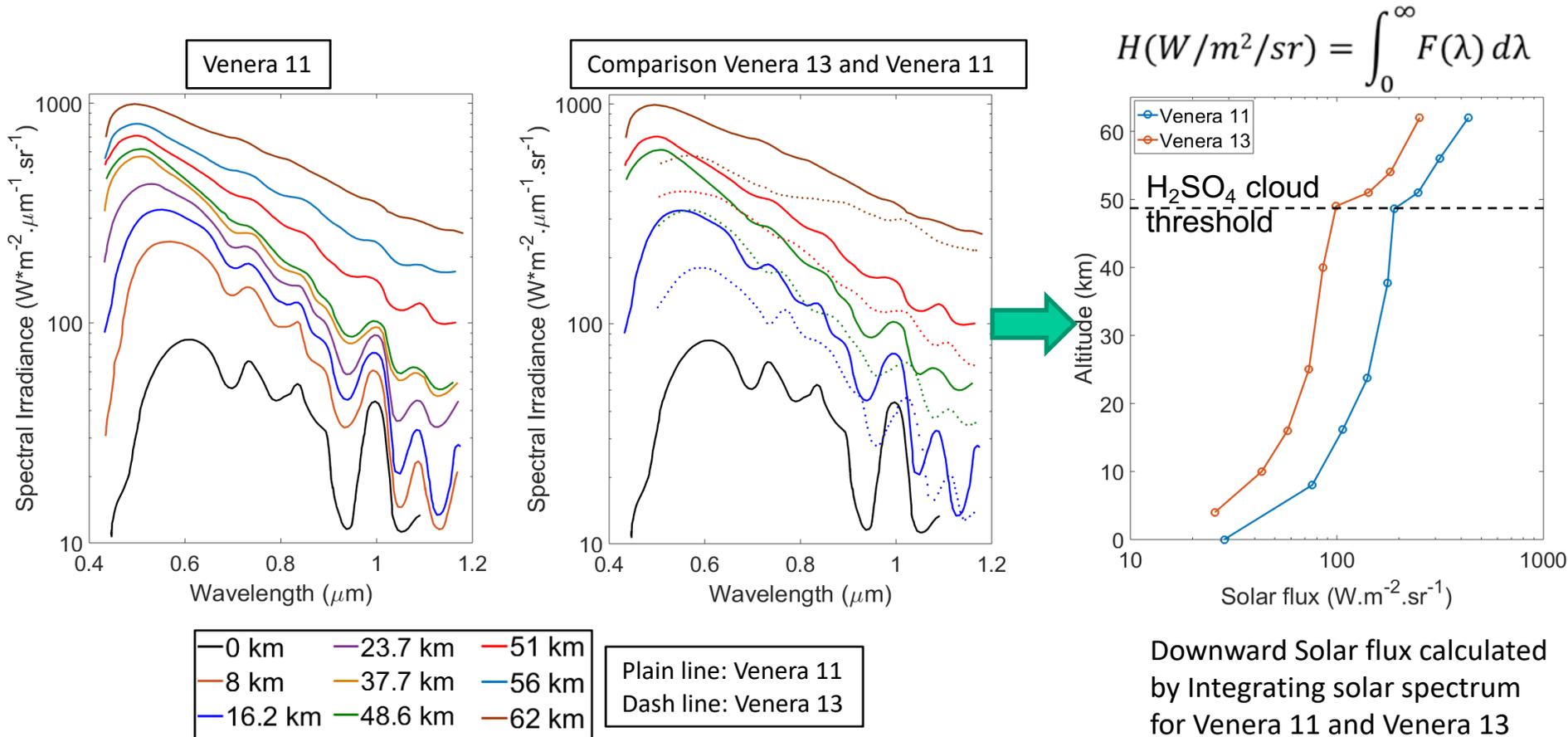


Courtesy  
NASA/JPL-Caltech.

# Venus atmosphere and solar illumination

Venus spectrum is very different from Earth and altitude dependent

Solar zenith angle 17 degrees (Venera 11) and solar zenith angle 38 degrees (Venera 13) changes the path length by ~20%, but there is an optical depth 25-40 H<sub>2</sub>SO<sub>4</sub> that accounts for a factor of 1.8 in radiance.



— 0 km	— 23.7 km	— 51 km
— 8 km	— 37.7 km	— 56 km
— 16.2 km	— 48.6 km	— 62 km

Plain line: Venera 11  
Dash line: Venera 13

Venus solar spectrum at various altitudes of Venus measured by Venera 11 and Venera 13 descent probes.

Downward Solar flux calculated by Integrating solar spectrum for Venera 11 and Venera 13 descent probes.

# Solar cell performance under Venus temperature and solar spectrum

**Corrosion protection.**

The cell is coated with an Al<sub>2</sub>O<sub>3</sub> layer to prevent corrosion from sulfuric acid.

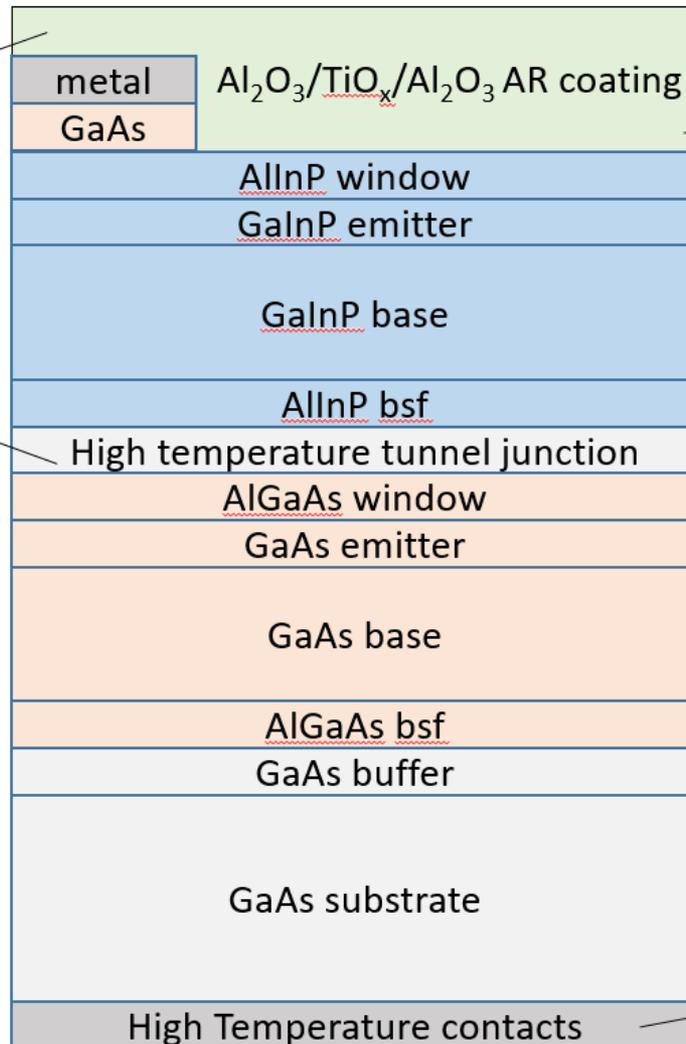
**Tunnel junction**

demonstrated to yield stable operation at 400°C

**Optimized bandgap.**

The top and bottom subcell bandgaps and thicknesses are adjusted to optimize efficiency at Venus.

Not to scale



**Anti-reflection coating (ARC).**

Window layer coated with Al<sub>2</sub>O<sub>3</sub>/TiO<sub>x</sub> ARC stable at 450°C

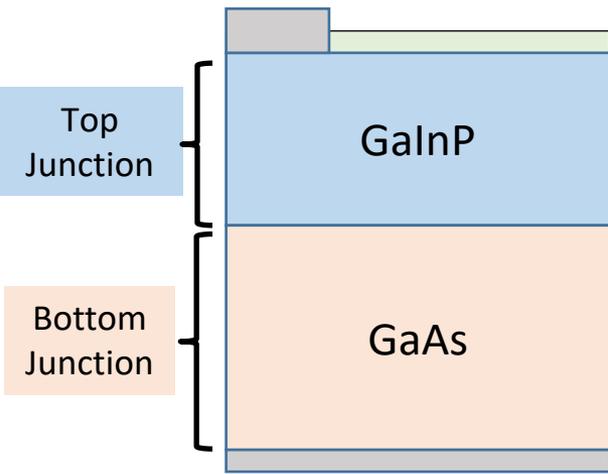
**Top subcell**

**Bottom subcell**

**High temperature contacts.** Ohmic contact (top and bottom) designs that are thermally stable up to 450°C

Y. Sun et al., "Thermal stability of GaAs solar cells for high temperature applications," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, 2016, pp. 2385-2388.

# Solar cell performance under Venus temperature and solar spectrum



Current:

$$J_{solar}(\lambda) = N_0(\lambda) * e^-$$

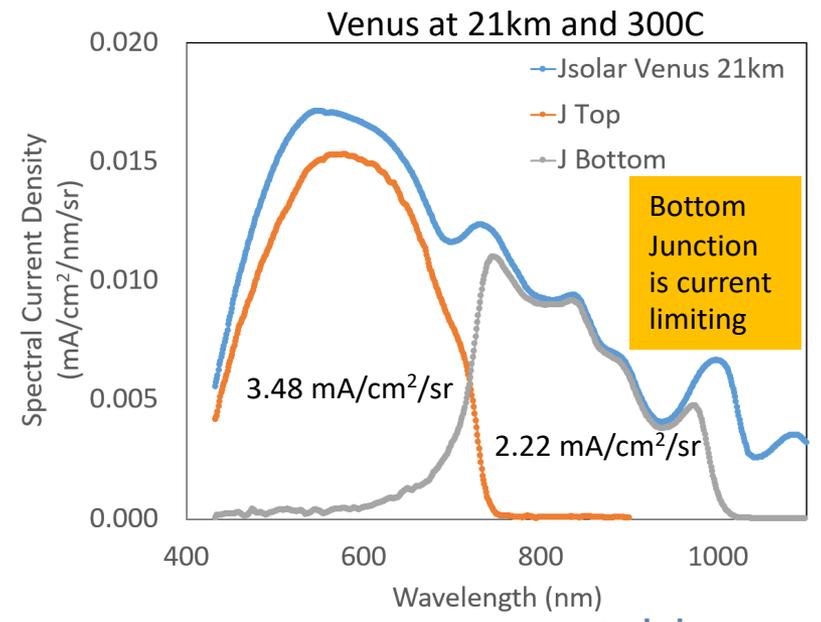
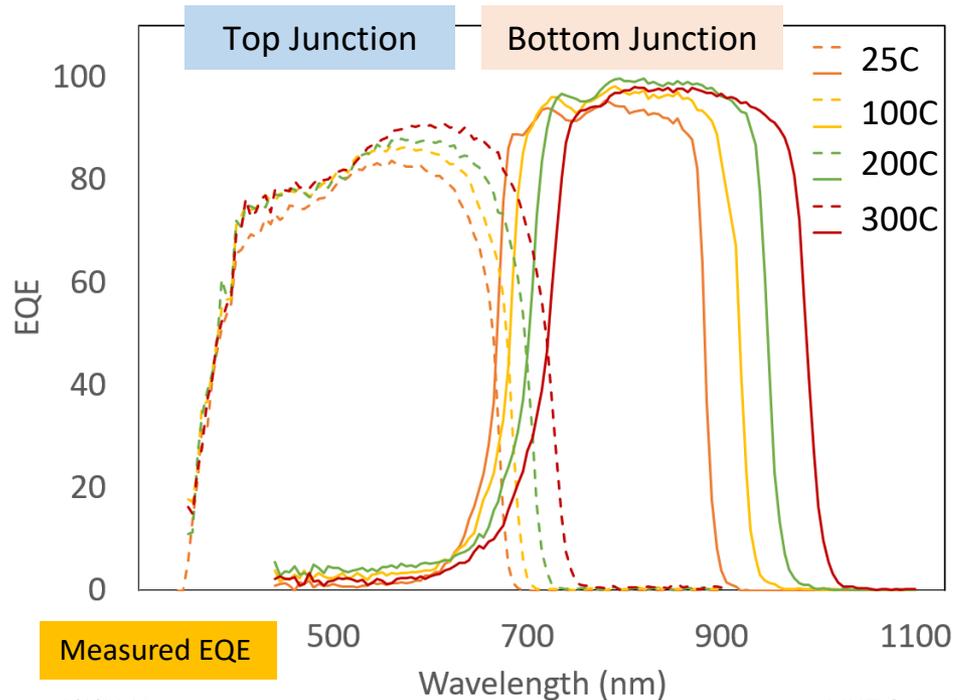
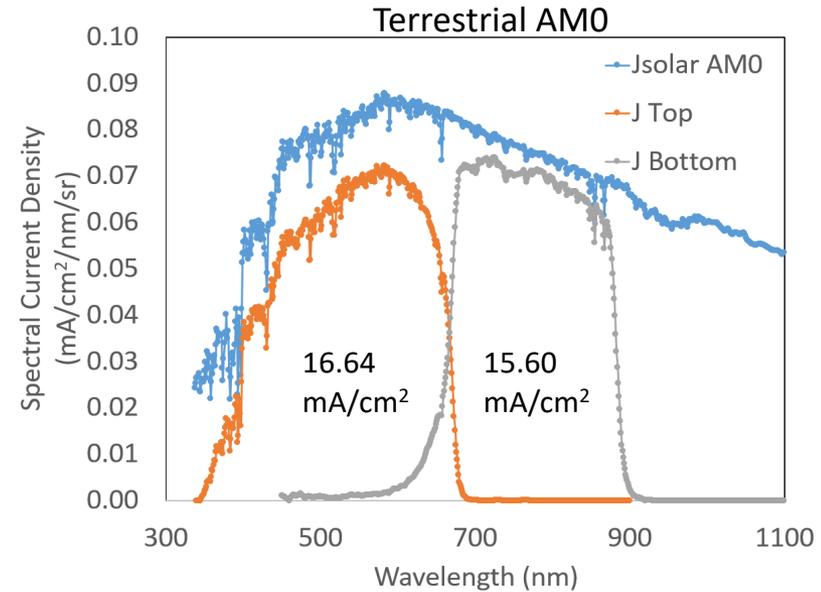
$$J_{ph} = EQE * J_{solar}(\lambda)$$

With Incident photon flux:

$$N_0(\lambda) = \frac{P_{solar}(\lambda)}{E_{ph}(\lambda)}$$

And photon energy:

$$E_{ph}(\lambda) = hc/\lambda$$

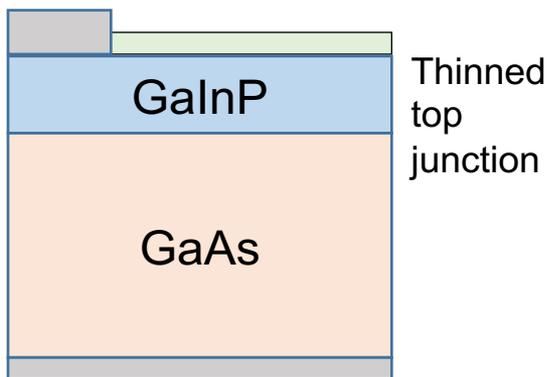


# Solar cell performance under Venus temperature and solar spectrum

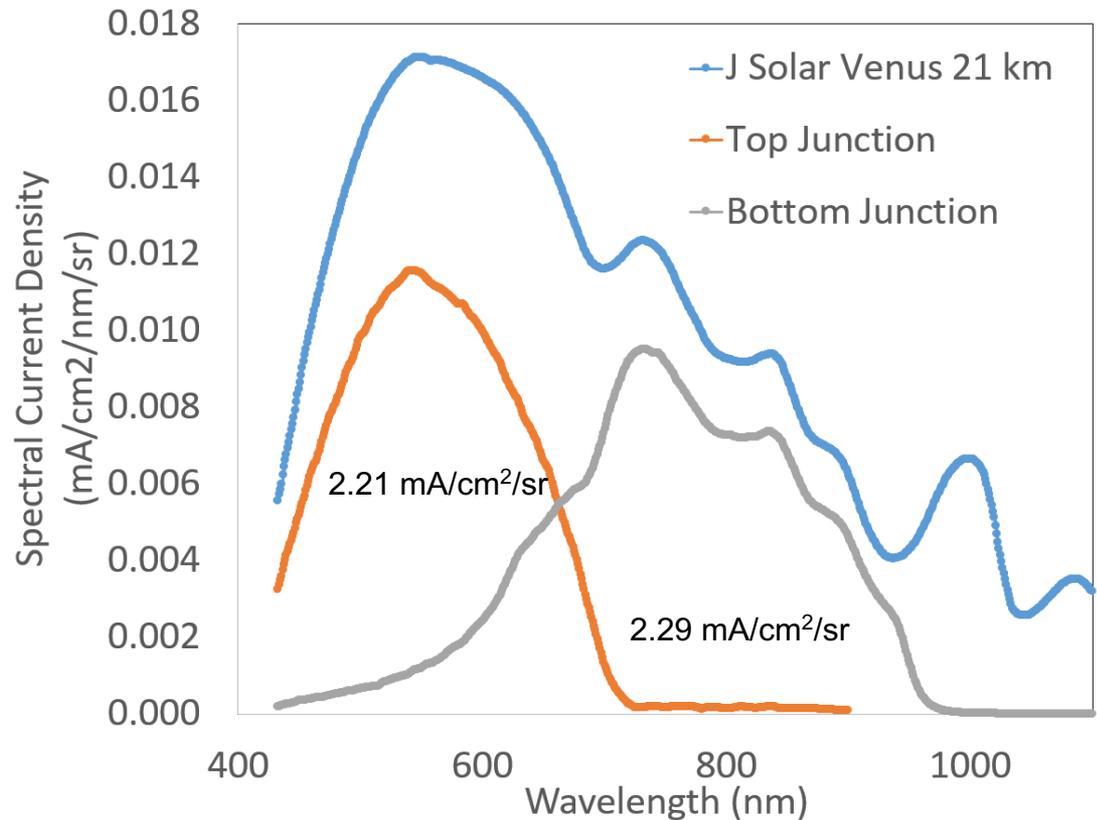
Gen 1



Gen 2



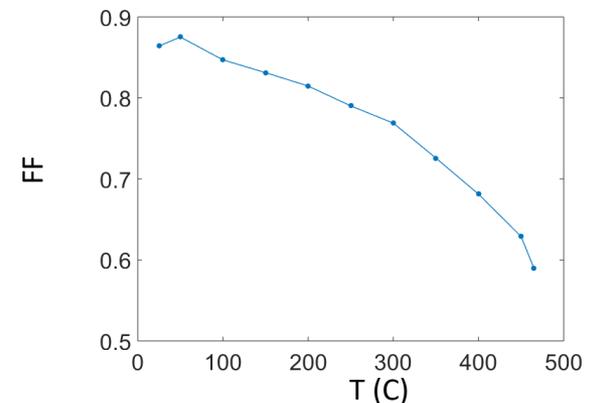
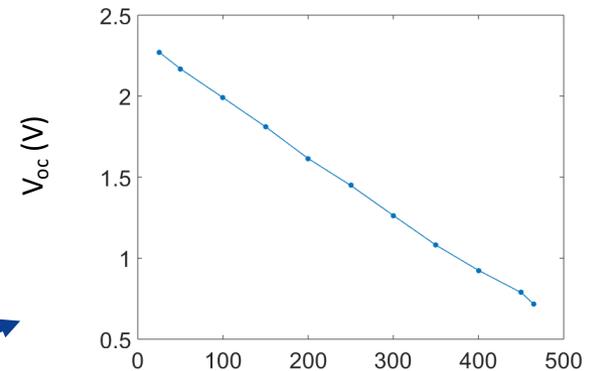
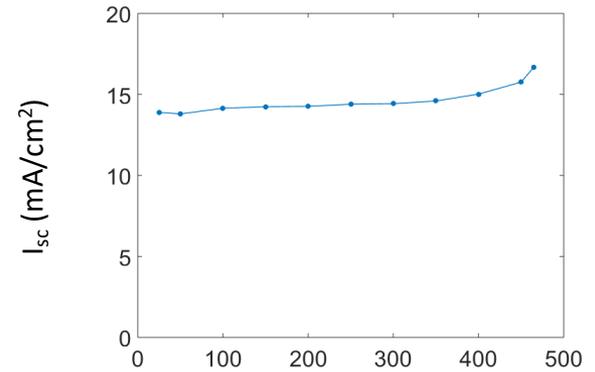
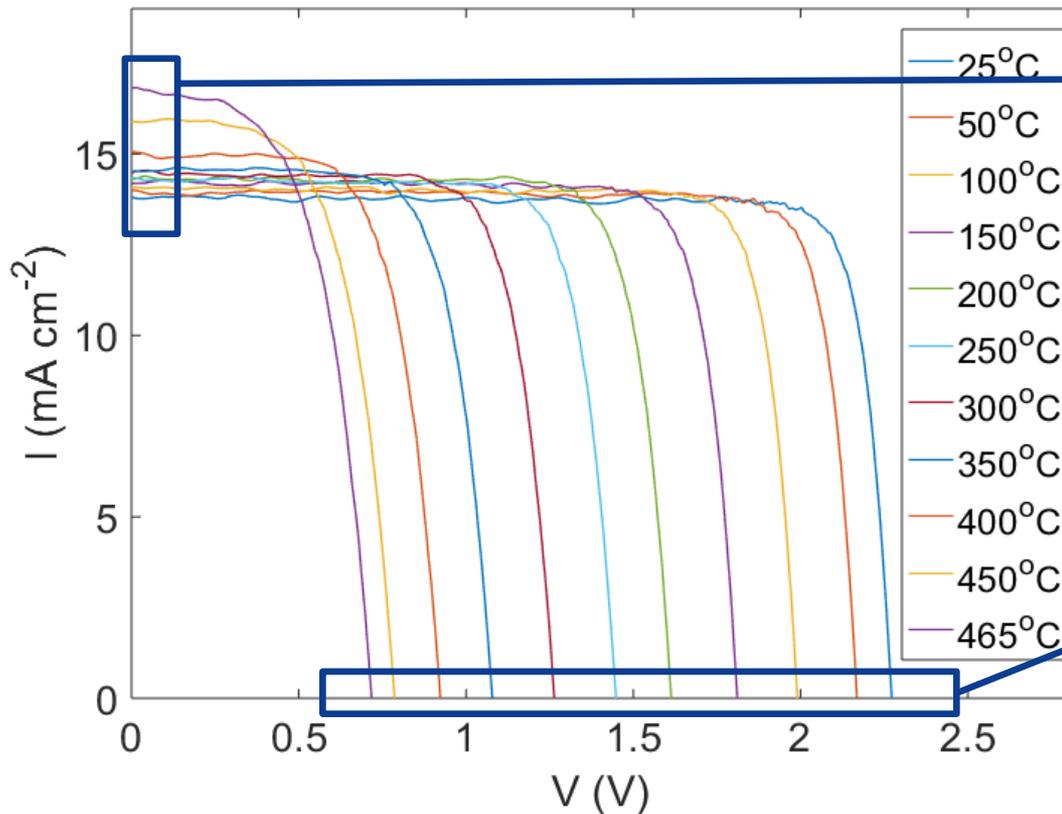
Both junctions are current balanced under Venus 21 km solar spectrum at 300C



Solar cell design is optimized for Venus 21 km solar spectrum and 300C.

# Solar cell performance under Venus temperature and solar spectrum

Temperature dependence of the solar cell between room temperature and 465C (Venus Surface)



JPL test capability simulates Venus temperature conditions

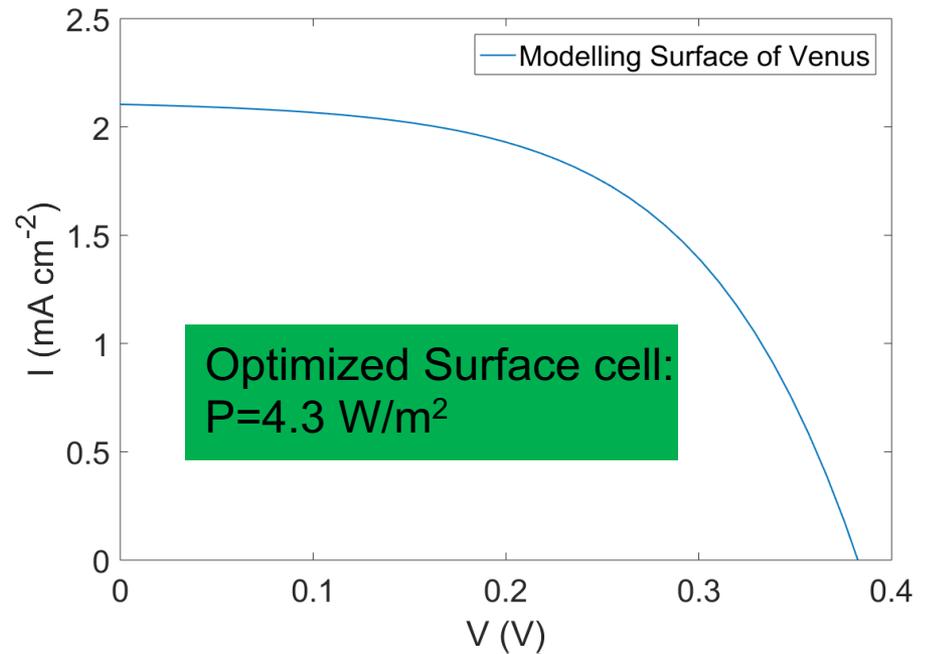
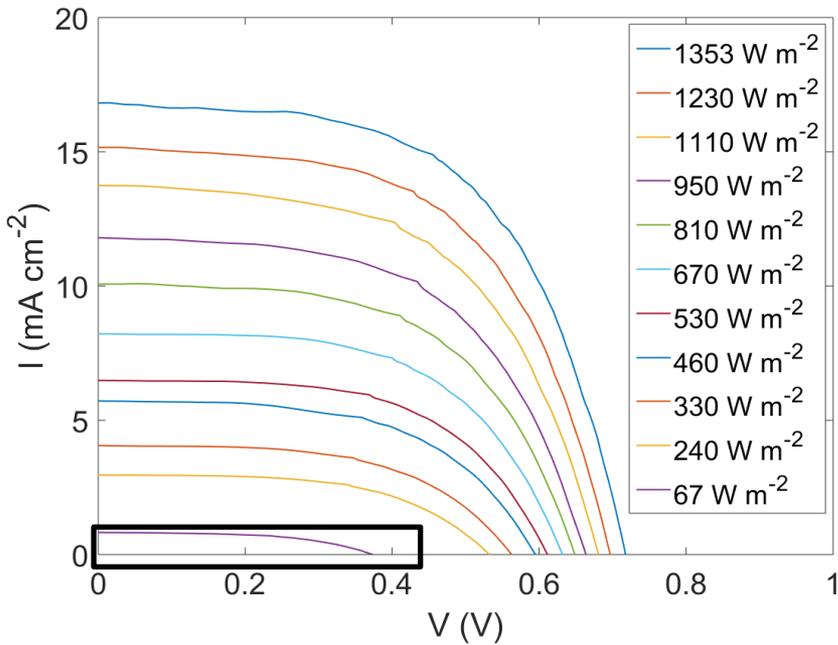
# Solar cell measurements under Venus conditions

Light I-V at 465°C between 1-Sun and 67 W/m<sup>2</sup> (Surface of Venus)

465°C (surface of Venus)

Measurement between 1353 W/m<sup>2</sup> and 67 W/m<sup>2</sup> (surface of Venus)

Modeling Optimized Surface:  
 GaInP/GaAs 2J solar cell  
 Voc=380 mV  
 Isc= 2.1 mA/cm<sup>2</sup>  
 FF=54%  
 η= 7%



Accounts for diffused light incidence angle  
 Could be increased by taking advantage of upward flux.

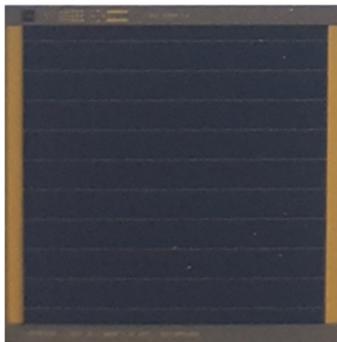
# Lifetime testing for survivability at Venus

Metallization 1 and 3 are Ag based

Metallization 2 and 4 are Al based

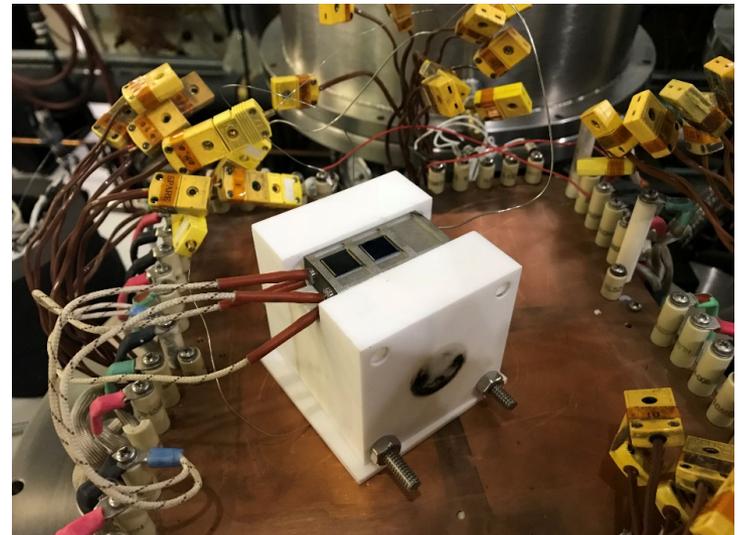
	465°C Venus Surface
24h	Metallization 1
1 week	Metallization 2
2 weeks	Metallization 3
1 month	Metallization 4

Metallization 3 and 4 processes were improved for high temperature.



1 cm<sup>2</sup> fabricated solar cell

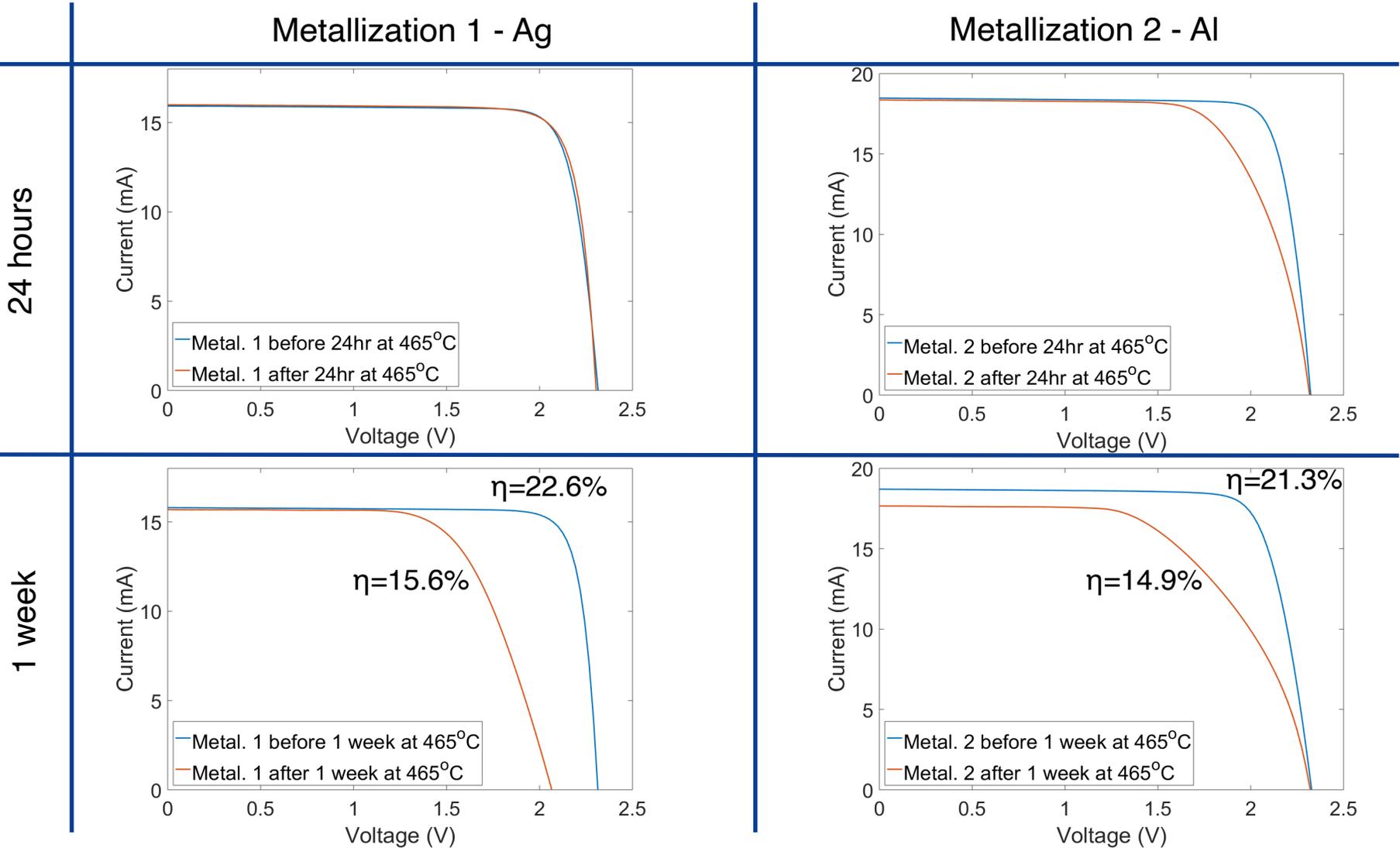
Lifetime Testing setup.  
Developed and designed at JPL



Bare solar cells were heated at 465°C (Venus surface temperature) under high vacuum 10<sup>-7</sup> Torr.

# Lifetime testing for survivability at Venus

I-V Before and After 1 week at 465°C AM0 1-Sun Light I-V Measurements at MLD

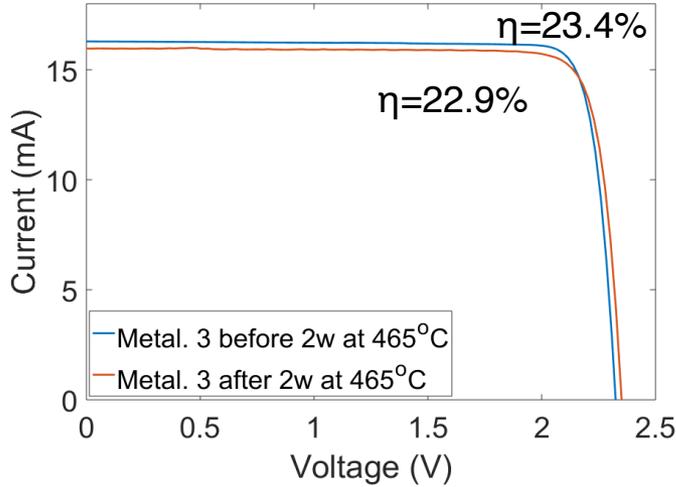


# Lifetime testing for survivability at Venus

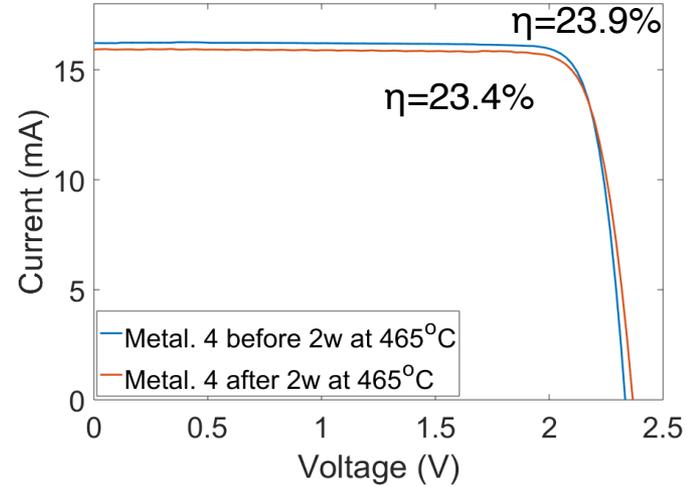
I-V Before and After 1week at 465°C AM0 1-Sun Light I-V Measurements at MLD

2 weeks

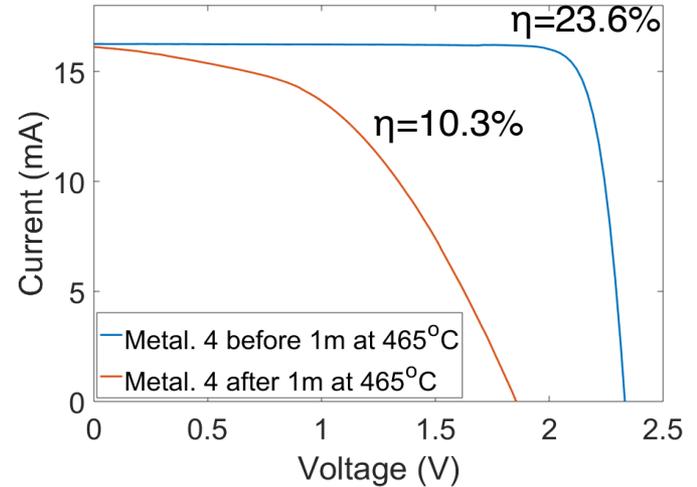
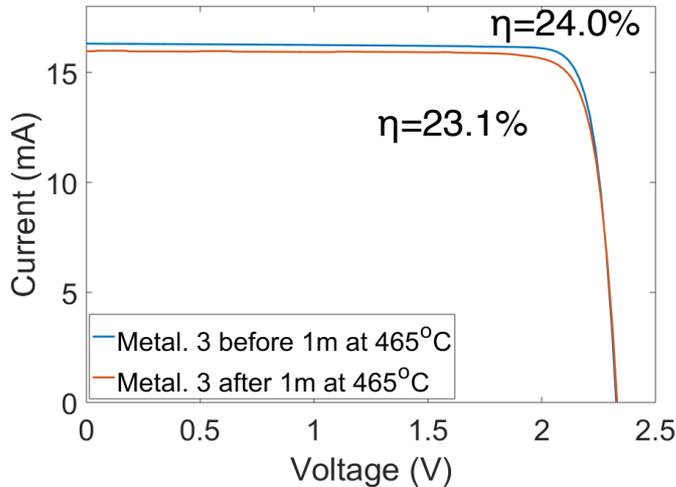
Metallization 3 - Ag



Metallization 4 - Al



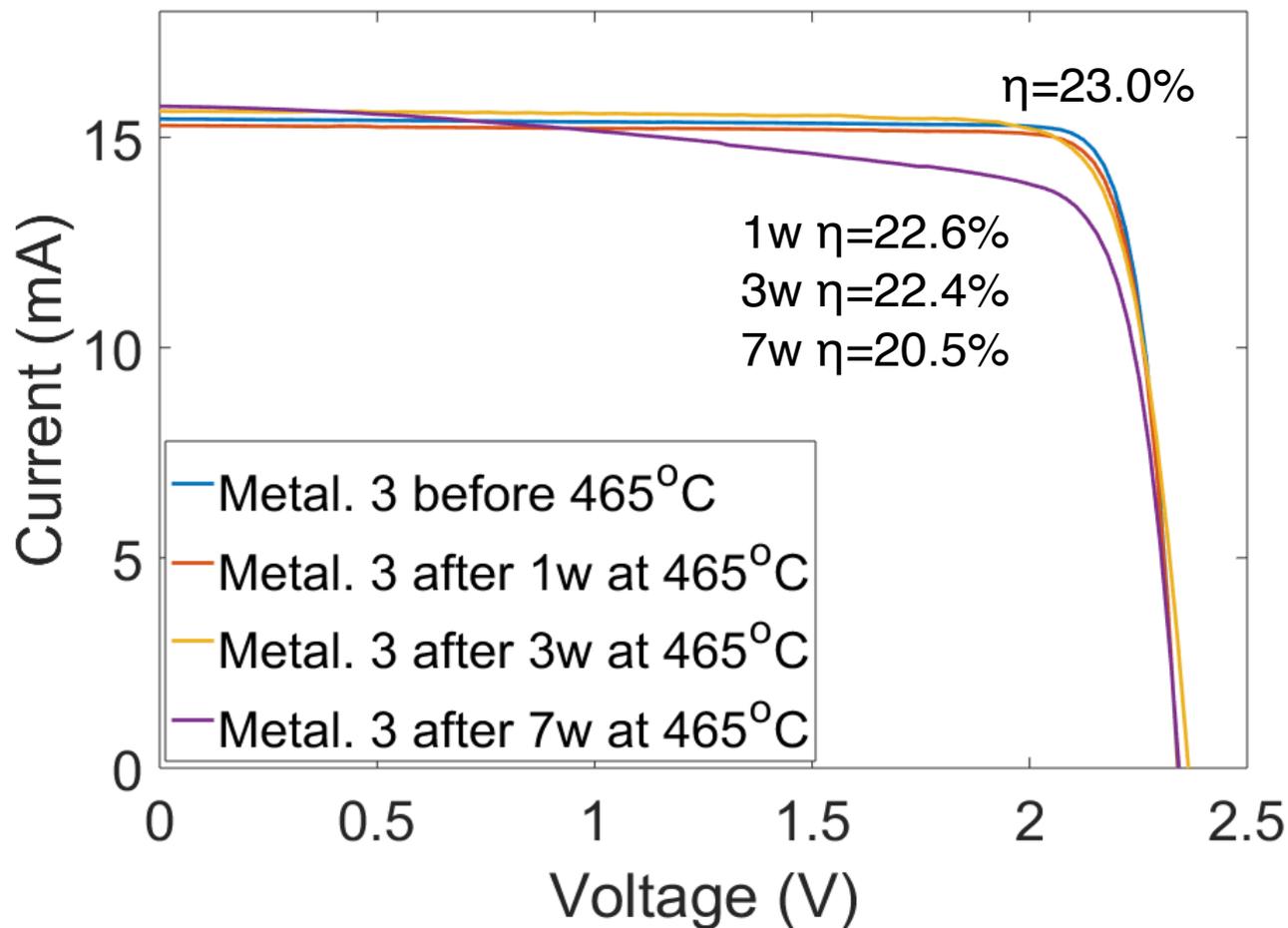
1 month



# Lifetime testing for survivability at Venus

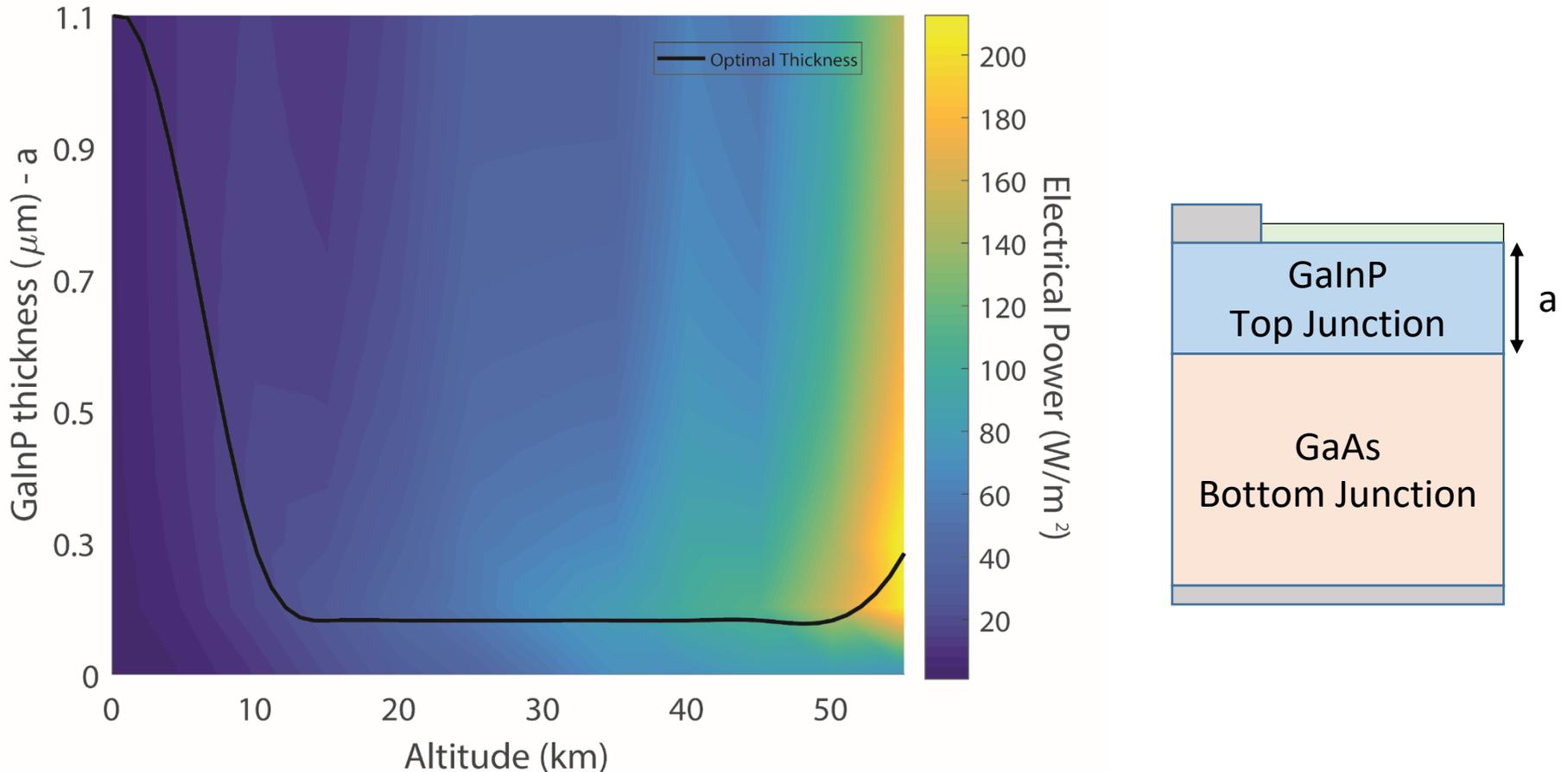
I-V Before and After 1 week, 3 weeks, and 7 weeks at 465°C AM0

1-Sun Light I-V Measurements at MLD



# Solar cell modelling for Venus Atmosphere (Caltech)

Electrical Power output for a dual junction GaInP/GaAs solar cell as a function of altitude and top junction thickness. The black line shows the optimal thickness at a given altitude.



# Conclusion

- Venus solar spectrum and temperature vary significantly with altitude.
- Solar cell was designed for a particular Venus spectrum and temperature – 21 km Venus Solar Spectrum and 300C.
- Solar cell with High Temperature metallization survived for 1 months at 465C without degradation and 7 weeks with limited degradation.
- Modelling shows an optimal design for a dual junction InGaP/GaAs solar cell at various Venus altitudes for varying spectra and temperatures.

## Future work:

- Design high temperature packaging for Venus corrosive environment

J. Grandidier, A. P. Kirk, M. L. Osowski, P. K. Gogna, S. Fan, M. L. Lee, *et al.*, “Low-Intensity High-Temperature (LIHT) Solar Cells for Venus Atmosphere,” *IEEE Journal of Photovoltaics*, vol. **8**, pp. 1621-1626, 2018.

# Acknowledgements

Jonathan Grandidier  
jonathan.Grandidier@jpl.nasa.gov



**Jet Propulsion Laboratory**  
California Institute of Technology

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